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Summary

The interference to television reception in the future from large wind turbine generators is discussed and methods for estimating the effect from proposed installations are presented, The results of some measurements in the field are given. These show that potential interference to viewers may occur in certain areas if the plans of the Electricity Generating Authorities to build large wind generators come to fruition.

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1. Introduction

Amongst the various alternative sources of energy for the generation of electricity that have been proposed and considered, wind power appears to offer the best hope of providing a useful contribution to the supply grid in some areas of the United Kingdom. The Central Electricity Generating Board (CEGB), which covers England and Wales, and the North of Scotland Hydro Electric Board (NSHEB) are actively pursuing the subject and planning some experimental pilot installations. The machines will be very large (about 100 m high) and will present a potential source of interference to broadcast services, especially to terrestrial television services in Bands IV and V.

The Electricity Generating Authorities are aware of this problem and it is hoped that they will continue to keep in touch with broadcasters as the project develops and consult with them regarding the possible degradation to broadcast services caused by wind-power installations at proposed sites. The other planning constraints on siting installations will include the need for favourable meterological conditions and general environmental considerations.

The large wind turbine machines will act as sources of re-radiation to produce delayed 'ghost' signals which can be modulated in amplitude by the rotation of the blades. The effect of pulsating 'ghosts' on a television picture is likely to be more disturbing than a constant 'ghost' of the same mean magnitude.

As always with reflected signals, the directivity of the viewer's antenna is of the greatest importance. Large wind generators that are approximately on the opposite azimuthal bearing from the television transmitter but are not too close may well cause acceptably low levels of interference.

Situations to be avoided are those where the wind turbines stand on high ground overlooking a community of viewers and where the viewer's antennas are pointed so that the re-radiated signals arrive in the principal lobe. The likelihood here is that the high ground will partially screen the viewers from the direct signal whereas the turbines will be in a region of relatively high signal strength; also antennas will not provide discrimination against the strong reflected signals.

Future work will probably fall into two main categories:-

(1) Planning estimates of interference problems in the neighbourhood of projected CEGB installations. Where existing transmitters are involved the estimates can be backed up by field strength measurements at the proposed site and in the local community.

(2) Measurement of re-radiation properties of actual wind machines.

Preliminary work has already been undertaken on both these fronts and is reported here together with a simplified theory that is adequate for making planning estimates.

2. Theory

2.1. Re-radiation due to turbine blades

A reflecting or re-radiating object not only scatters the incident signal but may cause depolarization. If however, the viewer's antenna has reasonable discrimination against the orthogonal polarization, the scattered cross-polarized component may usually be ignored.

In order to estimate the scattering effect of the blades it is sufficient to assume a representative but simple geometrical shape for them. It is possible that the aerofoil shape of the blades will be made from a non-conducting material such as glass fibre built around a supporting metal lattice structure. Alternatively the blades may be all-steel to give then flexibility.

The first approach looked at was to represent the blades by a conducting circular cylinder. Unfortunately the appropriate dimensions in wavelengths at u.h.f. are large so that the modal series in cylindrical co-ordinates is very slowly converging. A previous approach[1] has been, in this case, to consider the cylinder as a curved mirror (geometrical optics solution) or, when the cylinder is directly between the source and observer, as a flat diffracting plate with

with dimensions of the cylinder cross-section.

Another study[2] has used a flat conducting plate representation for the blades and this approach appears to bring out the main feature of the situation. Because of its relative simplicity and because only planning estimates are aimed at, this latter method is adopted here. To represent a two-bladed machine the plate is assumed to rotate about, and be perpendicular to, a horizontal axis through its centre.

2.2. Re-radiation from a flat plate model of the blades

Plane-earth geometry may be used for relations between distance and angles. This is illustrated in Fig. 1 where S is the source (transmitter), V a viewer and R the wind generator.

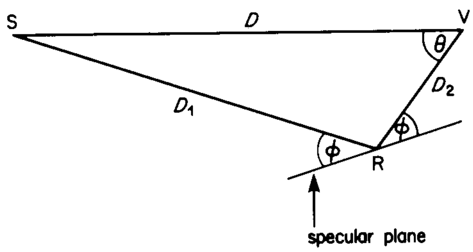


Fig. 1 — Path geometry.

The viewer's antenna is directed along VS. Because his antenna is assumed to be directional, small values of the angle θ (<20 degrees) will be of considerable importance.

The amplitude of the re-radiated signal will be greatest when the plane in which the blades rotate is oriented so that the angles of incidence and reflection (ϕ) are equal. This is called the 'specular reflection' condition. Because the machine will turn into the wind about a vertical axis, specular reflection will occur for some proportion of the time.

To cover the case where reflections have the most serious effect, specular reflection is assumed. In estimating the re-radiated field strength, the following simplifications can be made:

(1) The observer at V (the viewer) can be assumed to be in the far field of the re-radiated signal (see Appendix 8.1.)

(2) As the dimensions of the reflecting plate are large compared with the wavelength, the strength of the reflected signal can be assumed to be independant of the polarization of the incident wave.

With these simplifications, the magnitude of the re-radiated free-space field E_r (V/m) is given by:-

$$E_r = \frac{E\,A\,\sin\phi}{\lambda D_2} \times 10^{-3} \qquad (1)$$

where

E = strength of incident wave, V/m.

A = area of plate, m^2.

λ = wavelength, m.

D_2 = distance between wind generator and viewer, km.

The angle ϕ is shown in Fig. 1. If additional loss, such as diffraction or clutter loss, is expected on the path of the re-radiated signal then the value of E_r must be reduced accordingly.

2.3. Re-radiation by the support structure

So far, re-radiation from the support structure has not been mentioned. This will probably be a large lattice or concrete tower of height 50 m or more.

The time delay of this component of the received field will be approximately the same as that from the blades as far as the distance separation of the 'ghost' image from the main image on the received picture is concerned. However, the relative phase of the two interfering components will be significant and the visible effect will be controlled by the relative phases of the three incoming signals.

The magnitude of the re-radiated signal from the support structure will depend on its size and form; whether it is a lattice or concrete tower for example. However, it is reasonable to assume that it will be of the same order of magnitude as that from the blades when the specular condition obtains, whatever the polarization of the incident signal.

If equal signals from the support structure and the blades happen to arrive in phase an increase of 6 dB occurs. However, as this is an unlikely occurence, an increase of 3 dB in the value of E_r should be sufficient to take account of the presence of the support structure. With this assumption, Equation (1) can be re-written.

$$E_r = \frac{\sqrt{2}\ E\,A\sin\phi}{\lambda D_2} \times 10^{-3} \qquad (2)$$

It will be seen that Equation (2) goes to zero with ϕ but when ϕ is near to zero the viewer, the wind turbine and the wanted transmitter will be approximately in line. Then if the wind turbine turns through 90° from the specular reflection condition it will act as an additional obstruction in the path of the wanted signal and will only, in general, reduce the wanted field strength. This shadowing effect will probably be less significant than the generation of delayed signals in causing picture degradation and for the present will be ignored. Nevertheless, it will be desirable, when possible, to measure the shadowing effect of actual machines.

3. The planning assessment

This Section describes procedures for assessing interference from proposed installations. Section 3.1. describes a method which can be used when field-strength measurements can be made, while Section 3.2. describes a method for estimating the interference level when measurements are not available. Both methods provide estimates of the ratio between the wanted and re-radiated signals at the receiver input terminals. Since the visibility of delayed images is somewhat dependant on time delay, a formula for calculating the time delay is given in Section 3.3.

3.1. Assessment based on field-strength measurements

Field-strength measurements are made at or near the proposed wind generator site. Height gain should be applied so as to estimate the field strength at, say, the centre of the blades. This is the value of E in Equation (2), which is then used to calculate the re-radiated field strength E_r at the receiving site. An allowance should be made for diffraction losses if the path between the wind

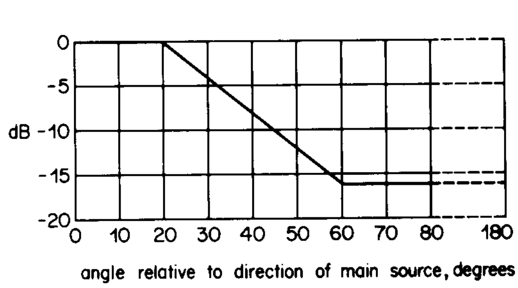


Fig. 2 – CCIR directivity curve of domestic receiving aerials used in Bands IV and V.

generator and the receiving aerial is obstructed. In calculating the ratio between the wanted and unwanted signals at the receiver input terminals, an allowance should also be made for the directivity of the viewer's receiving aerial, which may be assumed to be correctly oriented for reception of the wanted signal. The CCIR curve[3] for Bands IV and V, shown in Fig. 2, may be used for this purpose.

An example of this method of assessment is contained in Section 5.

3.2. Theoretical assessment

In the absence of measurements the ratio G (dB) between the wanted and unwanted signals at the receiver input terminals may be estimated from the following equation:

$$G = 10\log(P_w/P_r) + 20\log D - L + L_1 + L_2 + R \qquad (3)$$

where

P_w = e.r.p. of transmitter in direction of receiver

P_r = e.r.p. of transmitter in direction of wind generator

D = distance between transmitter and receiver, km

L = diffraction loss on transmitter-receiver path, dB

L_1 = diffraction loss between transmitter and wind generator, dB

L_2 = diffraction loss between wind generator and receiver, dB

R = re-radiation factor, dB, discussed below

P_w and P_r must, of course, be expressed in the same units.

In the absence of diffraction losses, and for an omnidirectional transmitting aerial, Equation (3) simplifies to:

$$G = 20\log D + R \qquad (4)$$

The calculation of R is described in Appendix 8.2. Fig. 3 shows values for R for a range of values of θ (see Fig. 1) expressed in terms of the distance ratio D_2/D. The curves apply to a

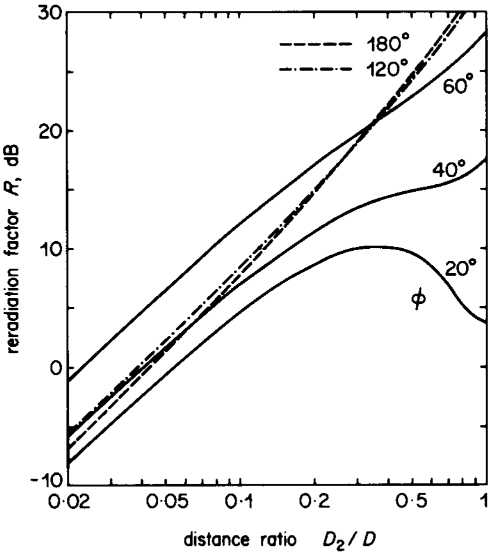


Fig. 3 — Re-radiation factor.

Curves valid provided $D_2 > 1km$.

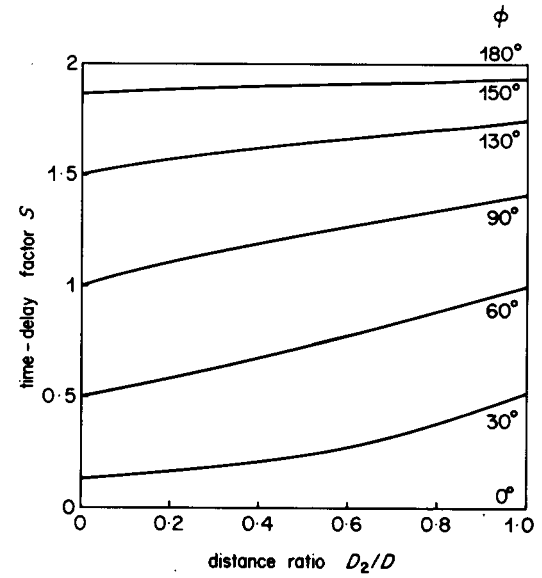


Fig. 4 — Time-delay factor.

Time delay = 3.33 SD_2 µs.

reflecting area A of 100 m^2 and a frequency of 600 MHz (λ = 0.5 m) but curves for other values of A and λ would be similar. The horizontal directivity of the viewer's receiving aerial, which is assumed to be correctly oriented for reception of the direct signal, is taken into account by means of the CCIR curve shown in Fig. 2. As a result of this directivity, R increases progressively for values of θ greater than 20°, up to θ = 60°. Beyond 60° the receiving aerial gives no additional rejection of the unwanted signal and R then tends to decrease, because the reflecting surface becomes more nearly normal to the incident radiation as θ approaches 180°. Fig. 3 shows that, with the assumptions made, the strength of the re-radiated signal which would be received if the wind generator where behind the viewer's aerial would be almost as great as that which would be experienced if θ = 20°.

3.3. Time delay

The re-radiated signal arrives with a time delay which is proportional to the path difference $D_1 + D_2 - D$ (see Fig. 1). The delay time can be readily calculated, given the angle θ and the distance ratio D_2/D, with the help of Fig. 4, which gives values for a factor S; the time delay is then equal to 3.33 SD_2 µs, where D_2 is in km.

4. Modulation by blade rotation

In general the amplitude of the re-radiated signal, as received, will be modulated by the rotation of the blades. Speeds of up to one rotation per second are to be expected so that fundamental modulation frequencies of up to 2 Hz will occur for two-bladed machines.

4.1. Measurement of modulation

The simplified model, the rectangular metallic plate to represent the blades, leads to a peaky modulation envelope for the reflected signal at angles away from the specular reflection condition. This fact is born out by measurement. Some exploratory observations have been made close to a wind generator at Boroughbridge (South Yorks) using the horizontally polarized transmissions from Belmont. This is a three-bladed machine and relatively small compared to the proposed high-power machines. It is an experimental horizontal axis machine having three blades, each about 8 metres in length, consisting of a steel supporting structure covered by a glass fibre aerofoil.

Fig. 5 gives sketches of some examples of the field variation at a receiver in the neighbourhood of the generator. In order to examine the variation, it is desirable to attempt to isolate the reflected signal. Difficulty was experienced in reducing the wanted signal to a low enough relative level. The method adopted was to search for positions where, with the receiving antenna directed towards the wind machine, the signals from the distant transmitter were minimized by antenna rejection. By experimenting at a number

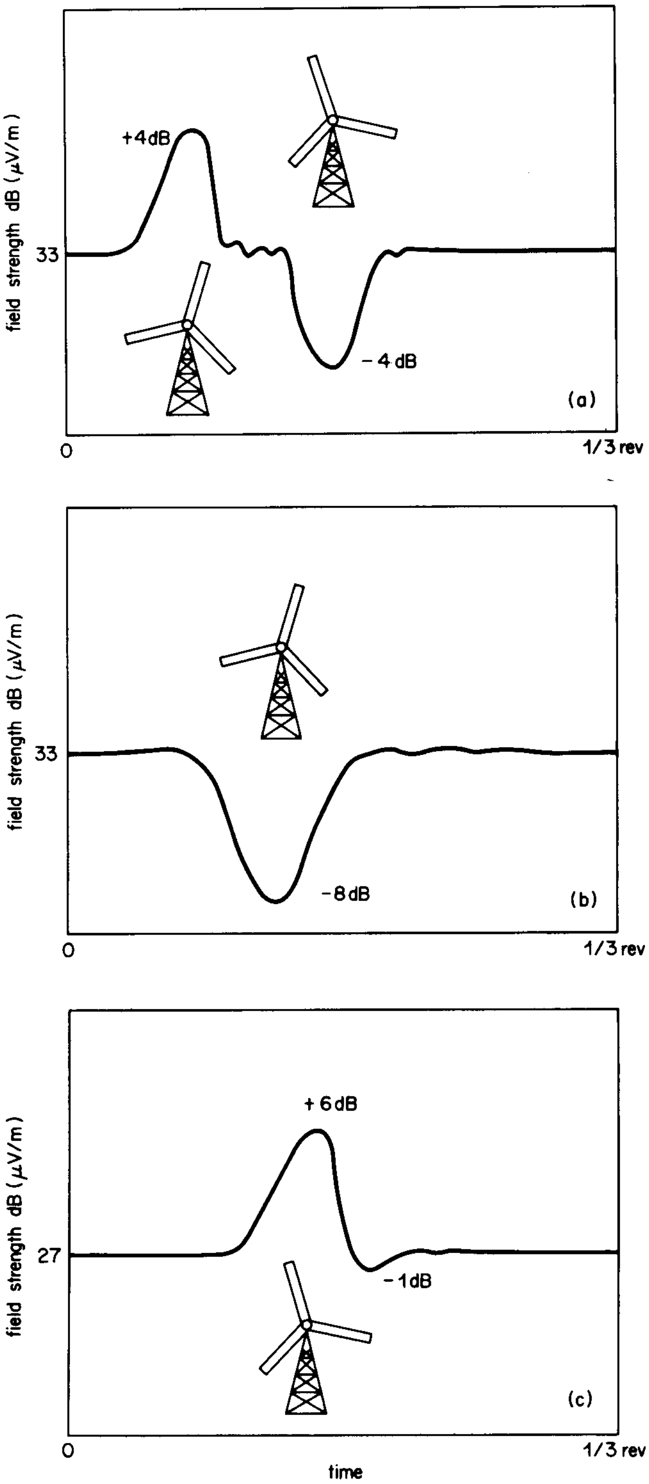


Fig. 5 — Modulation of signal reflected by generator blades.

(a) Channel 22; receiving antenna 10 m. above ground, vertically polarized.

(b) Channel 25; receiving antenna 3 m. above ground, vertically polarized.

(c) Channel 32; receiving antenna 3 m. above ground, horizontally polarized.

of points and adjusting antenna height to take advantage of a minimum in the standing wave pattern, reductions of the direct signal of 30 dB or more were possible at a few points. At most points it was necessary to cross-polarize the antenna to achieve adequate reduction.

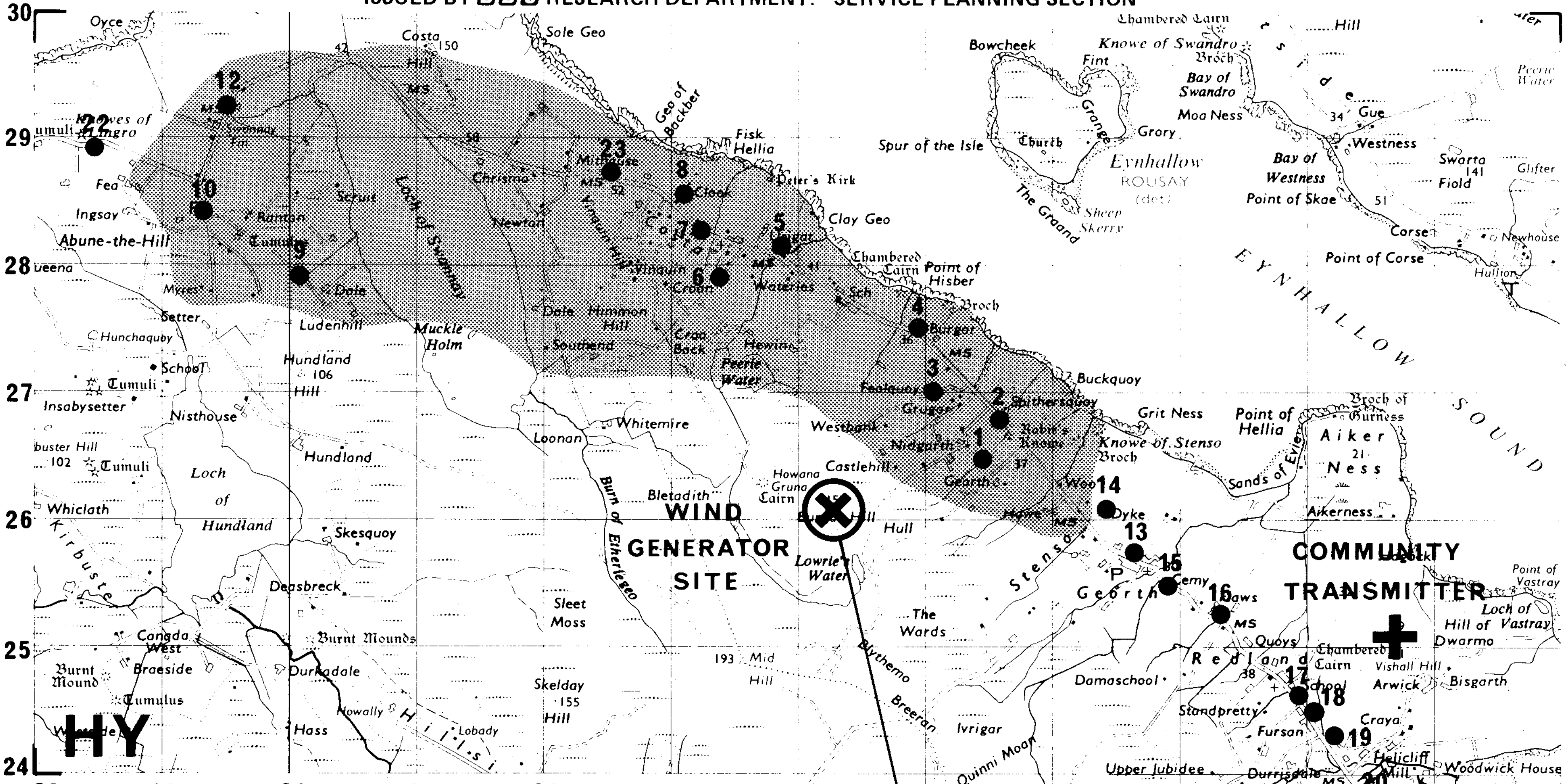
Despite the difficulties the tests served to show the variations of the interfering component that can occur when the blades rotate. From the curves in Fig. 5 it can be seen that the peak amplitude of the reflected component was of the order of 27 dB (μV/m).

5. Tests at Burgar Hill

The North of Scotland Hydro Electric Board propose to construct two wind driven turbines based on two-bladed horizontal axis rotors at Burgar Hill in the Orkney Islands, at the location shown in Fig. 6. The tips of the blades of the small machine will describe a 20 m diameter circle and those of the large machine a 60 m diameter circle. The blades, which will be constructed of tubular steel with a glass fibre coating, will have rotation speeds of approximately 5 turns every 4 seconds for the small machine and 1 turn every 2 seconds for the large machine. Site work is now in progress and the approximate time scale for completion is one year for the small machine and three to four years for the large machine.

The u.h.f. broadcast services in the area are provided by the transmitter at Keelylang Hill. There is a small community-operated transmitter at Vishall Hill which provides an alternative service to most viewers south of Burgar Hill. Measurements were carried out in the area to enable an assessment of be made of interference to viewers using Keelylang Hill. These were made at 10 m a.g.l. at positions as close as possible to viewer's installations. The field strength from Keelylang Hill and picture grade were recorded at each point. The test points are shown in Fig. 6, numbered from 1 to 23, and the measured results are given in Appendix 8.3.

The path profile between the Keelylang Hill transmitter and Burgar Hill is shown in Fig. 7. The measured field strength of Keelylang Hill at the site is approximately 83 dB (μV/m) at 10 m a.g.l. and it is predicted that the signal level will be significantly higher at and above the centre of 60 m diameter machine. For the assessment of interference 94 dB (μV/m) has been taken as the amplitude of the incident field and the blade area (A) assumed to be 100 m^2. All installations in



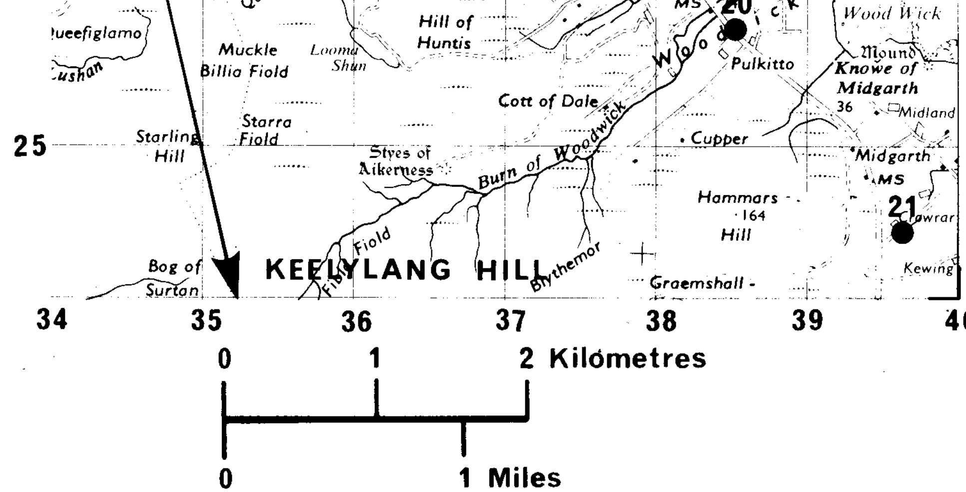


FIG 6

MAP OF FIELD TEST AREA

MAP KEY

● 10 Locations of measurements. See the appendix

Area likely to be affected by delayed image interference from the blades of a wind driven turbine generator on Burgar Hill.

Topographical information derived from O.S. sheet No. 6

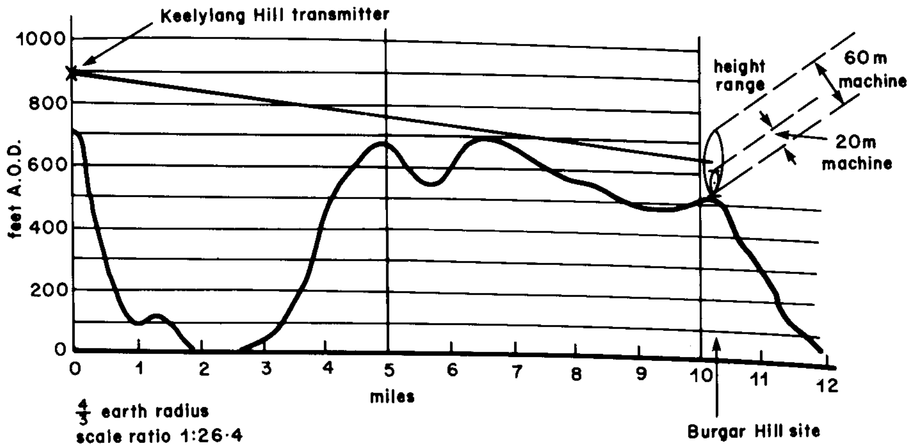


Fig. 7 – Ground profile: Keelylang Hill to Burgar Hill

the district are line of sight to Burgar Hill and there are no terrain losses.

At location 23, ϕ = 10° and D_2 = 3.2 km. For λ = 0.45 m, Equation (2) gives an unwanted field strength of 59 dB (μV/m). The amplitude of the direct signal at location 23 from Keelylang Hill is 70 dB (μV/m). The aerial directivity of a typical domestic aerial is given in Fig. 2; at location 23 the difference in bearing between Keelylang Hill and Burgar Hill is only about 20° and no allowance can be made.

Therefore, at the receiver input, the interfering signal will be 11 dB below the wanted signal. The visibility of delayed image signals is somewhat dependent on the time delay, but if the delay is more than 0.75μ sec. a difference of about 30 dB between signals is required for a grade 5 picture. The calculated time delay between the signals at location 23 is 1.7μ sec. and it is almost certain that reflections from the blades will result in grade 2 to 3 interference. The rotating blades will cause pulsating interference which is likely to be more annoying to viewers than a steady level delayed image.

From an analysis of the measurements given in Appendix 8.3. it is predicted that the blades of the 60 m machine will cause delayed images at some 65 installations within the shaded area of Fig. 6. The field strength of Keelylang Hill at all but one of these locations is below the nominal limit of 70 dB (μV/m) for broadcast services. However, almost all the viewers have installed better than average receiving systems and it is estimated that about 50% of them can receive satisfactory pictures which are better than grade 3 (see Appendix 8.3.). The predicted additional pulsating interference from the 60 m wind turbine will undoubtedly result in complaints from these viewers. For the remaining 50% reception is already very difficult because of low field strengths and reflections from the surrounding terrain and the additional interference will be much less troublesome.

Interference from the 20 m machine will be significantly less for two reasons. The incident signal will be lower because the signal path to Keelylang Hill is obstructed and the blade area is smaller; both factors will result in a total reduction of about 15 dB in the reflected signal.

6. Conclusions

The large wind turbine generators being proposed by the Electricity Generating Authorities could cause unacceptable interference to television viewers in some parts of the United Kingdom. A short field investigation near a proposed site in the Orkney Islands has shown that some viewers in the neighbourhood of the machine are likely to be affected. This conclusion is based on a simplified method for calculating the levels of re-radiated signals but this method is not likely to be so much in error that the conclusion is invalid.

It may be argued that, from the point of view of householders, the degradation of the terrestrial television service should be considered as an environmental issue that is given equal weight to aesthetics, loss of amenities etc. Representation by broadcasters at public enquiries, when these are held, would seem to be a desirable aim. Co-operation may be needed in difficult cases to ensure that provision can be made for additional relay stations or wired systems to overcome any degradation of the service.

In Section 3.2. a planning curve is given which can be used for quick estimates of interference if, for example, the effect of several proposed wind machine sites in an area is being considered.

7. References

1. KNIGHT, P., 1966. Re-radiation from masts and similar obstacles at radio frequencies. *Proc. Instn. elect. Engrs.,* 1967, **114,** pp. 30 - 42.

2. SENGUPTA, D.L. *and* SENIOR T.B.A. Electromagnetic interference by wind turbine generators. U.S. Department of Energy, Report TID-28828. March 1978.

3. Directivity of antennas in the reception of broadcast sound and television. *CCIR Recommendation* 419, (XVth Plenary Assembly 1982 Vol XI Part 1 p.236).

Appendices

8.1. The far-field approximation

The assumption made in Section 2.2. that the viewer is in the far field of the re-radiated signal requires that his distance from the wind turbine is sufficiently great. This distance, in turn, depends on the size of the machine.

Consider the flat plate model, (30 m x 3 m) illuminated at normal incidence by a plane wave. The far-field estimate assumes that the re-radiated contributions from all parts of the plate arrive at the viewer's antenna in phase.

If the distance is too small the phase variation caused by path difference from points on the plate will modify the result and Equations (1) and (2) will over estimate the re-radiated signal strength. The error incurred may be estimated, with the aid of Fresnel integrals, as a function of distance; values are given in the Table below.

Distance (km)	Error (dB)
0.5	+3.4
1.0	+0.8
1.5	+0.4

As distances of importance will be generally greater than 1 km, the assumption can be justified.

8.2. The re-radiation factor

This appendix describes the derivation of the re-radiation factor R used in the theoretical assessment method (see Section 3.2.).

The field strength F_w at the receiver, due to the wanted signal, in dB (μV/m), may be expressed in the form

$$F_w = K + 10 \log P_w - 20 \log D - L \tag{5}$$

where K is a constant and the other symbols are defined in Section 3.2. Similarly, the field strength F in dB (μV/m) at the wind generator is given by:-

$$F = K + 10 \log P_r - 20 \log D_1 - L_1 \tag{6}$$

Now Equation (2) in Section 2, which describes the re-radiated signal, may be expressed in decibels as follows:-

$$F_r = F + 20 \log \frac{A \sin\phi}{\lambda D_2} - L_2 - 57 \tag{7}$$

where

$$F_r = 20 \log E_r$$
$$F = 20 \log E$$

F_r is the field strength at the viewer's aerial due to re-radiation and F is given by Equation (6). All other symbols are defined in Sections 2 and 3.2.

The difference G (dB) between the wanted and unwanted signals at the receiver input terminal is:-

$$G = F_w - F_r - H \tag{8}$$

where H is the horizontal directivity factor (dB) of the receiving aerial, given by Fig. 2.

Substitution of Equations (5), (6) and (7) in Equation (8), followed by comparison with Equation (3), leads to the following expression for the re-radiation factor R.

$$R = 20 \log (D_1/D) + 20 \log (D_2/D) - 20 \log \frac{A \sin\phi}{\lambda} + 57 - H \tag{9}$$

8.3. Field strength measurement and picture grade assessments at locations near to Burgar Hill.

The measurements were made with a log-periodic antenna at 10 m a.g.l. and the pictures were viewed on a portable colour receiver. The transmitter was at Keelylang Hill, observations being made on Channels 40(BBC-1), 46 (BBC-2), 43(IBA). The results are summarised in the table which follows.

	TEST LOCATION	FIELD STRENGTH/GRADE*			COMMENTS
No.	Name	BBC-1	BBC-2	IBA	
1.	Eyin Helga, Evie	39/2	–	38/2	Very weak picture. Images up to 30μs
2.	Crugar	40/2	–	38/2	Very weak picture. Images up to 30μs
3.	Feolquoy	51/2	–	53/2	Multiple images up to 40μs
4.	Burgar	41/2	–	41/2	Weak picture. Images up to 40μs
5.	Urigar	46/2	–	43/2	Multiple images up to 30μs
6.	Quarryhouse, Costa	57/3	–	57/3	Grade 3 image at 1μs. Other images not worse than Grade 4
7.	Muckle Pow	62/4	–	62/4	Multiple images just perceptible
8.	Airsdale	48/3-4	–	50/3-4	Multiple images
9.	Belmont, Swannay	62/3	58/3	61/3	Multiple images up to 25μs

*CCIR 5-grade impairment scale.

Grade 5. Imperceptible.
Grade 4. Perceptible but not annoying.
Grade 3. Slightly annoying.
Grade 2. Annoying.
Grade 1. Very annoying.

	TEST LOCATION	FIELD STRENGTH/GRADE*			COMMENTS
No.	Name	BBC-1	BBC-2	IBA	
10.	Swannay Post Office	67/2	62/2	66/2	Grade 2 image at 30μs Multiple images Grade 3
11.	–		–	–	
12.	Menobreck	57/3-4	54/3-4	56/3-4	Multiple images up to 30μs
13.	Dale	51/2	–	49/2	Grade 2 image at 5μs. Other images up to 30μs
14.	Dyke Farm	53/2	–	53/2	Grade 2 image at 5μs. Other images up to 30μs
15.	No. 2 Council Houses	42/2	–	40/2	Grade 2 image at 5μs. Other images up to 30μs
16.	Flaws	51/2	–	48/2	Multiple images up to 24μs
17.	Evie School	74/7	–	75/4	Multiple images just perceptible
18.	North Wades	71/4	–	71/4	Multiple images just perceptible
19.	Horay Evie	66/4	–	68/4	Worst image Grade 4 at 2μs
20.	Woodwick Stores	56/2	48/2	48/2	Multiple images up to 30μs
21.	Crawrar	89/4	82/4	88/4	Image at 2μs
22.	Lingro	92/5	–	91/5	Good clean pictures.
23.	Mithouse	70/4	–	69/4	Multiple images just perceptible

*CCIR 5-grade impairment scale.

Grade 5. Imperceptible.
Grade 4. Perceptible but not annoying.
Grade 3. Slightly annoying.
Grade 2. Annoying.
Grade 1. Very annoying.